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A methodology to delineate protection zones in karst aquifers: The case of municipality of Kozani, North Greece

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Carbonate rocks in Greece occupy about 35% of the surface area of Greece and are mainly located in the western, central and southern parts of the country. The carbonate rocks can be divided into sedimentary formations (limestones and dolomites) and metamorphic rocks (marbles). They mainly date from the Triassic to the Cretaceous periods, whereas marbles have a Paleozoic-Mesozoic age. Within the carbonate rocks are hosted karst aquifers which are the main supply source for domestic use in many sites of Greece. However, integrated management plans of karst aquifers in Greece are only focused on extraction limitations, while detailed monitoring, vulnerability assessment and modelling are neglected. According to the EU Directives and new Greek legislation of management plans of aquifers in Greece require the determination of protection zones of springs and wells used for domestic uses.

The delineation of protection zones is not a straightforward and one-dimensional process. It should be a part of an integrated management plan of the aquifer system (Burgess and Fletcher, 1998). The process is much more difficult dealing with karst aquifer due to their anisotropy and uncertainty of their structure and function. A sustainable management of karst aquifers includes the following steps (Biava et al., 2014; Kazakis et al., 2018):

a) Detailed hydrogeological observations (temporal and spatial data).
b) Data analysis applying advanced statistical methods.
c) Application of integrated models depending.
d) Vulnerability and risk assessments.

Although in Greece, many studies deal with statistical analysis of karst systems (Panagopoulos and Lambrakis, 2006), vulnerability assessment (Kazakis et al., 2015; Nanou and Zagana, 2018) and time series analysis (Manakos et al., 2019) there is a methodological gap for the delineation of protection zones in Greek karst aquifers. It is pointed out that karst aquifers are highly vulnerable to pollution, precisely because of their specific structure (Biava et al., 2014).

In this study we suggest a methodological approach for the delineation of protection zones in karst aquifers. The process includes basic hydrogeological research, hydrochemical and isotopic analysis, statistical analysis, simulation process, and vulnerability and pollution risk assessment. Obviously, the delineation of the protection zones of the karst systems constitute the final step and maybe the most important step for the sustainability of the systems. In this study we provide the methodological framework in simple research steps in order to delineate protection zones to karst aquifers. This protocol has been developed during the study of four karst aquifers in the municipality of Kozani, in western Macedonia, north Greece (Fig. 1). The water demands of the municipality are covered by exploiting of these karst aquifers. Hence, the sustainability of these hydrosystems is of the outmost importance for the water security of the area. The suggested methodology to delineate protection zones in karst aquifers includes the following research steps:

Literature review: A detailed literature review of the existing geological and hydrogeological studies is essential for the delineation of protection zones. The literature review could provide the initial hydrogeological conceptual model of the karst aquifer, the missing data and determine the field work.

Data base development and digitization in Geographic Information System (GIS) environment: All available maps (geological, geomorphological, hydrogeological) including geological and hydrogeological information should be digitized. Hence, a data base can be created in G.I.S. environment in order to elaborate and analyse the various spatial data and create the corresponding thematic maps.

Hydrogeological observation: The hydrogeological research includes field measurements, data collection and analysis. More specific, field measurements include: a) hydrogeological-geological mapping of karst features, springs, aquifer boundaries, faults using both field measurements, satellite images and UAS (DRONE) images, b) geophysical research applying electrical resistivity tomographies in order to determine the structure of the aquifer, c) hydrochemical analysis to determine the quality of groundwater, and d) isotopic analysis of stable isotopes and tritium in order to determine the recharge zones and groundwater age.

Statistical analysis: The statistical analysis includes methods such as cross-correlation, autocorrelation and phase function of rainfall and discharge of the karst aquifer. The main contribution is to understand the functioning of the hydrosystem and determine the lag time of the system.

Modelling: The modelling process contributes in the prediction and exploitation of the quantities of the system. The modelling process include both lumped (e.g. Karstmod) and spatial models (e.g. Modflow-CFP).

Groundwater vulnerability and pollution risk assessment: The vulnerability and pollution risk assessment are the final step to delineate protection zones and suggest land use changes. The PaPRIKa method and the corresponding

plugin have been widely used for the vulnerability assessment of karst aquifers (Ollivier et al., 2019) and hence, it has been included in the suggested methodological approach.

The holistic approach of the suggested methodology can ensure high reliability in the delineation of protection zones in karst aquifers. It can be adopted in different hydrosystems according to the data availability. Additionally, the integrated approach of this method ensures the reliability of the results and the social acceptance of the protection zones. It should be mentioned that the application of different methods give different results as regards to the extension of the protection zones. Hence, the proposed methodology would be benefit by improvement in hydrological data monitoring and the application of isochrones method to compare the results.

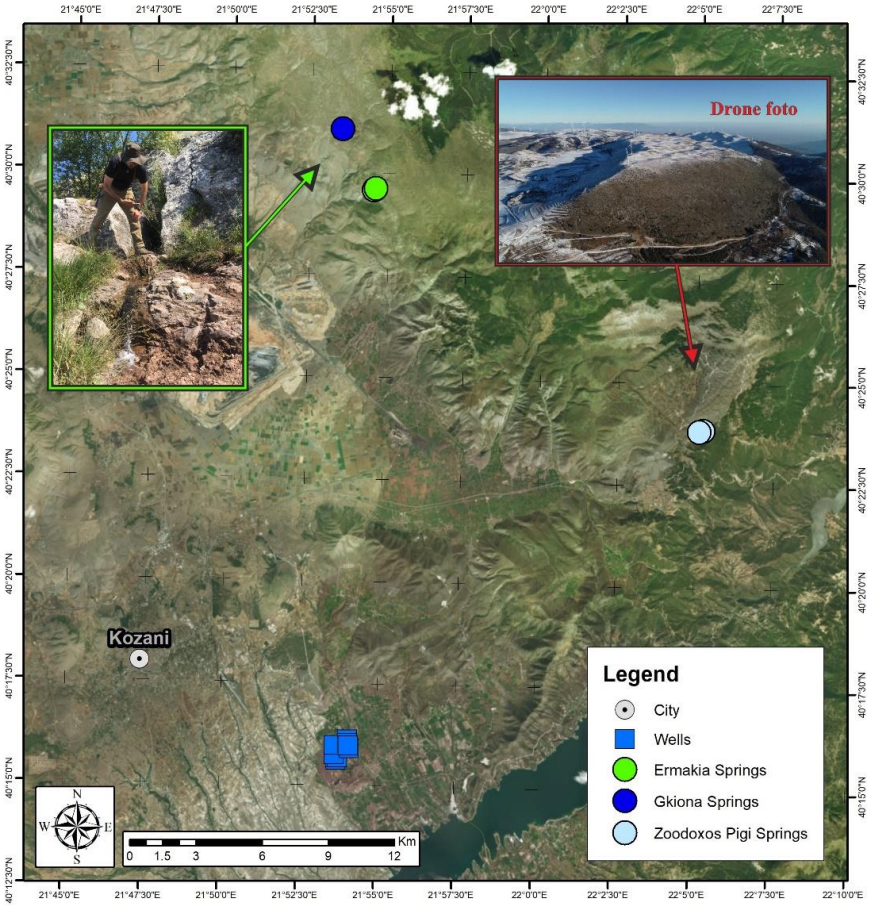

Figure 1. Karst aquifer systems in the Kozani region.

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